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Integrated design-oriented framework for Resource Selection in Additive Manufacturing

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Abstract

Resource selection (RS) is one of the prime phases of product design that have substantiating impact on the manufacturing of products. Material and manufacturing process selection are considered an important ingredient of RS and must be dealt with in early stages of design. Since, emerging technologies such as Additive Manufacturing (AM) have re-defined the potentials of manufacturing by re-orienting market drivers such as high part-complexity needs, individualization, shorter product development cycles, abundant materials and manufacturing processes, diverse streams of applications, etc., it is imperative to select the right compromise of materials, manufacturing processes and associated machines in early stages of design considering the Design for Additive Manufacturing guidelines. As several criteria, material attributes and process functionality requirements are involved for decision making in the industries today, an integrated design-oriented framework is proposed in this paper for RS in AM to structure design knowledge pertaining to each stage of design process; conceptual, embodiment and detail designs. However, more focus will be kept on the conceptual and embodiment design phases. Moreover, axioms are defined to aid in decision making and help in extracting the rules associated with each of the design criteria. The framework is aimed to act as a guideline for designers in the AM industry to provide design oriented and feasible material-machine-process combinations.

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Keywords: Additive manufacturing; Decision making; Integrated product-process design

1. Introduction

1.1. Motivation

Design of a product requires not only the satisfaction of requirements related to the functionality of the part, but also the realization of manufacturing process-related constraints. Since manufacturing is no more about building mere physical products, market drivers such as economics of production, mass customization, shorter lead times, improved business models, changes in consumer demands, nature of products, and broad areas of applications (aerospace, automotive, health care, etc.), have guided the stakeholders to take important decisions in early stages of design, and subsequently reduce the costs of assembly and logistics [1].

Additive Manufacturing (AM), over the years, has displayed the potential to build anything. AM is defined by American Society for Testing Materials (ASTM) as the "process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing technologies like traditional machining" [2]. Moreover, Monzon et al. [3] divided AM in to 7 distinct areas; vat photopolymerization, material jetting, powder bed fusion, binder jetting, material extrusion, sheet lamination, and directed energy deposition. For each of these 7 areas, the associated AM processes are many (Stereolithography, Fused Deposition Modeling, Selective Laser Sintering, etc.). Therefore, the constraints involved in 3D modeling procedures for each process, digitization of ideas [4], discretization of the produced parts, choosing the right balance of materials, manufacturing processes and AM machines, limitations in material selection, longer design cycle compared to manufacturing cycle, post processing and surface finish issues, etc., are few of the many factors the designers working in the AM industry must concentrate on today [5,6].

With various constraints, functional requirements, and design tradeoffs related to product performance, the AM designers have been convinced to use the Design for Additive

Manufacturing (DfAM) guidelines to develop an integrated approach in the design stage which can not only integrate design and manufacturing [referred to as Integrated Product Process Design (IPPD) from now on] but also cater for many manufacturing constraints and factors linked with traditional machining, such as avoiding separate fasteners, developing a modular design, using standard components, and minimizing assembly directions, to obtain parts of any geometric complexity without traditional machining aids such as tooling [7, 8, 9]. It is also imperative to understand here that as the design matures from preliminary level to full scale production, the freedom to change the design is decreased considerably. It further implies that DfAM becomes increasingly significant in the early phases of design as it can help in avoiding manufacturing pitfalls and maximize utilization of AM capability [10,11].

DfAM has been used in researches related to tool path optimization, part orientation, light weight design, and dimensional accuracy [12]. Yazdi et al. [13] used skin-skeleton model to integrate design and manufacturing via DfAM for topological optimization. Salonitis and Zarban [14] used multi criteria decision analysis to find one final design from a set of optimized designs via DfAM, too. Hence, considerable work can be seen in literature on the optimization of products and authors following either of the 'function-driven design strategy' or 'manufacturing-driven design strategy' [15] wherein more emphasis is put on the modification of Design for Manufacturing (DFM) for AM (DfAM) using a combination of design criteria (cost, environment, etc.). But such guidelines just provide a starting point and do not provide information related to AM machines and their production capabilities [16].

Resource Selection (RS) is an important phase of DFM. As AM itself has a healthy blend of processes, the suggestion of the correct combination of materials, manufacturing processes and associated machines, becomes an interdisciplinary effort considering AM's capability to be both inclined towards concurrent development (i.e., IPPD) and governing multiple areas of applications. Although AM has unlimited potential, but it doesn't guarantee having unlimited capability. The selected AM resource must satisfy requirements pertaining to product's lifecycle by considering factors such as design engineering, manufacturing, marketing, esthetics, reliability and quality [17].

As a usual practice, RS is conducted based on experience or knowledge of the designing/manufacturing personnel. Since, knowing everything by a person or a team is difficult, a comprehensive and robust selection system is necessary for the users to select a compromised AM material-process-machine combination(s) [18]. For the case of traditional or conventional manufacturing, various multi-criteria decision making (MCDM) methods have been proposed for RS, such as, Cambridge Engineering Selector (based on Ashby's material and process selection charts) [19], Case-based Reasoning (CBR) [20], material selection programs [21], Knowledge-based Systems (KBS) [22], etc. However, for the case of AM, different processes not only display considerable overlap in terms of possible applications, but also significant differences exist in terms of suitable materials and quality of printed parts [18]. Therefore, being a relatively new technology, most users do not have enough knowledge and experience to make good judgments for RS in AM. Mancanares et. al [23] used Analytical Hierarchy Process (AHP) to select AM processes based on the requirements generated from a part. Similarly, Armillotta [24] selected a suitable AM process from a set of alternatives for prototypes by using an adaptive AHP decision model. The attributes considered included fast build, good accuracy, and reduced material cost. This also open a window of opportunity to apply AHP in RS for AM since it is the most widely and successfully used MCDM method [25]. It is apparent from the literature reviewed that AHP has been applied extensively on not only small- and large-scale problems but also on those areas that have multiple criteria. Moreover, it is suitable for areas such as manufacturing sector since it relies on the innate human inclination to conduct comparison by considering both subjective and objective attributes [26]. It is applied to material selection in gears [27], selection of best material for design of lightweight aircraft metallic structures [28], selection of non-traditional machining processes in conceptual design stage for the body of modular hip joint endoprosthesis [29], and in material and process selection for a drilling grid in aerospace industry [25].

Having discussed the avenues of IPPD and RS for AM, it is now imperative to shed some light on the design cycle. The design activity can be divided into 3 main stages; conceptual, embodiment and detail designs. For each of the stages, the coupling between materials, component size and processes, cost interaction among processes, and sustainability indicators of materials, need to be considered [30]. Therefore, strategies such as rule-based system approach [31] have been widely used to help in knowledge acquisition, choosing the selection criteria, building hierarchical definition of knowledge, selection of a user interface, and finally the implementation. But prior to all this, it is necessary to capture the voice of the customer in terms of needs, specifications, aesthetic preferences, and constraints, to formulate requirements and functionality [32]. Few studies [30, 33] have worked on the RS in conceptual and embodiment design stages, respectively.

Considering the literature reviewed, it is evident that there is a need to rely on a systematic approach for RS in AM to capture the design requirements and structure the design knowledge for each stage of design process. Secondly, since RS is best dealt by decision making and as multiple criteria and attributes related to both product and process are involved, guidelines or axioms need to be defined from the literature reviewed to aid in decision making for each of the design criteria. Moreover, the approach in this paper compliments the existing methodologies and further attempts to develop a knowledge management system that can gather and provide feasible material-machine-process combinations for AM designers. The research is a first step towards a holistic approach to support RS in AM.

1.2. Structure

The remainder of the paper is divided as follows: Section 2 explains the proposed methodology by focusing on structuring the design knowledge for decision making in each of the conceptual and embodiment design stages; Section 3 attempts to validate the 'decision-making' part of the framework by using an example; and finally, Section 4 discusses the conclusions drawn.

2. Integrated design-oriented framework for RS in AM

The integrated design-oriented framework proposed in this paper follows a step by step procedure for RS (material, machine and process selection) in AM. The framework is globally impacted by the DfAM guidelines and application type, and locally follows three major steps; translation, screening and ranking. It considers 3 design criteria; function, cost and environment. It also shows an interaction with 2 independent databases; one for the AM materials and the second for AM process-machine combinations. To decrease the cost related to manufacturability of a part, the proposed framework further works deeply in the conceptual and embodiment design phases with respect to decision-making in each phase. Furthermore, to structure the decision hierarchy, the framework explores the potentials of AM and suggests respective measures with the help of reviewed literature (see Fig. 1). The inner circle represents the potentials of AM such as complexity for free, individualization, etc., while the outer circle shows the measures that need to be taken to achieve each of the shown potentials.

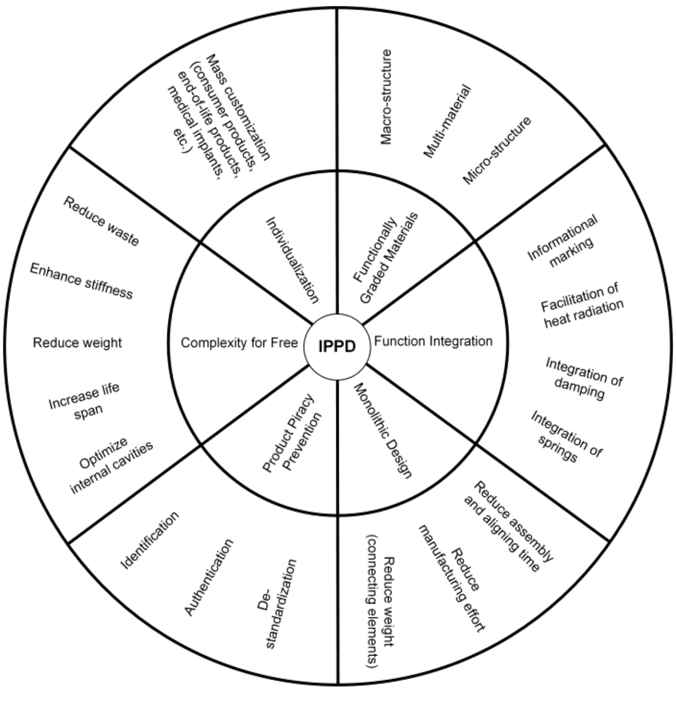

Fig. 1. Potentials and respective measures of AM (developed by authors)

Fig. 2 shows the global view of the proposed framework with the shaded boxes containing avenues for decision-making with respect to RS. Conceptual design, in context of IPPD, is considered the key stage of design process where the designer explores the fundamental scientific principles, DfAM guidelines, constraints, and associated relations, to structure an embodiment that can realize later in a design that satisfies the floated need. Next, the embodiment design stage allows for the application of MCDM tools (AHP and Ashby material/process selection charts) and any associated cost models for selection

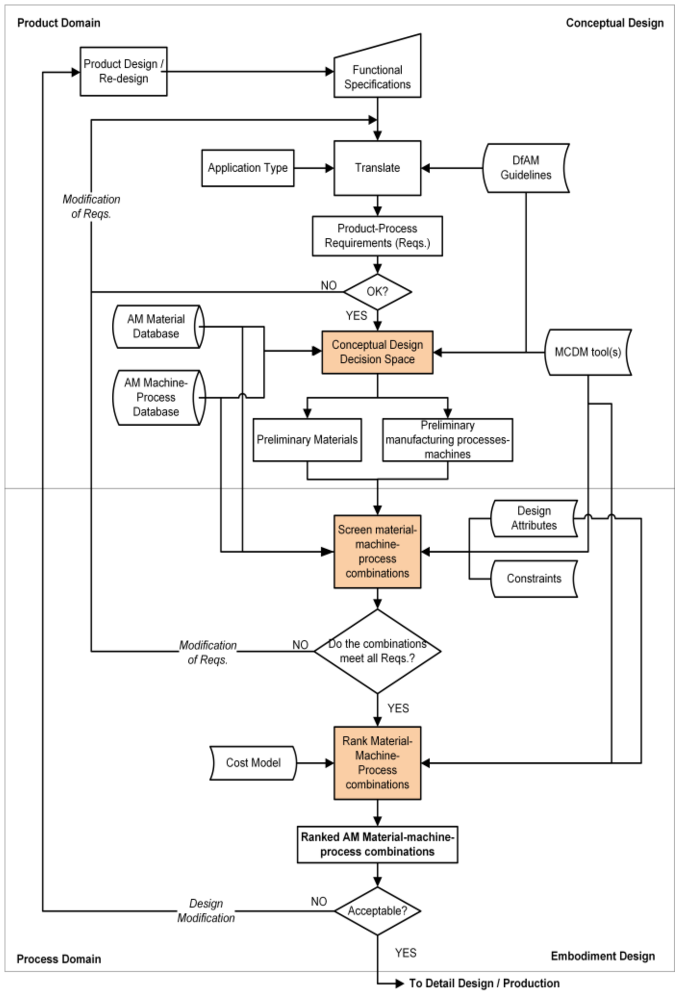

Fig. 2. Integrated design-oriented framework for RS in AM

of the compromised set of resources for AM, based on design attributes and functional constraints.

The text to follow will explore avenues of decision making in each of the design stages. Also, an example of how axioms are defined for one design criteria; environment, will be shown along with the mechanism to extract rules.

2.1. RS in Conceptual Design

In the context of the proposed framework, once the set of requirements are generated (design-, production-, and/or process-related), the information is routed to the “Conceptual design decision space” (see Fig. 2). Since decision-making in the development of products requires collaboration among different teams, the knowledge generated must be managed in a way that a compromised, yet ‘win-win’ solution is available for all stakeholders [33]. The decision space is shown in Fig. 3.

Each of the design criteria are associated with unique decisions that act as selection fronts for the RS. They are termed as technical decisions, economic decisions and sustainability decisions, respectively. Technical decisions are related to the performance of the product; viability and cost preferences are governed by the economic decisions; while sustainability decisions are related to environmental impact of AM materials in terms of landfill waste and recyclability.

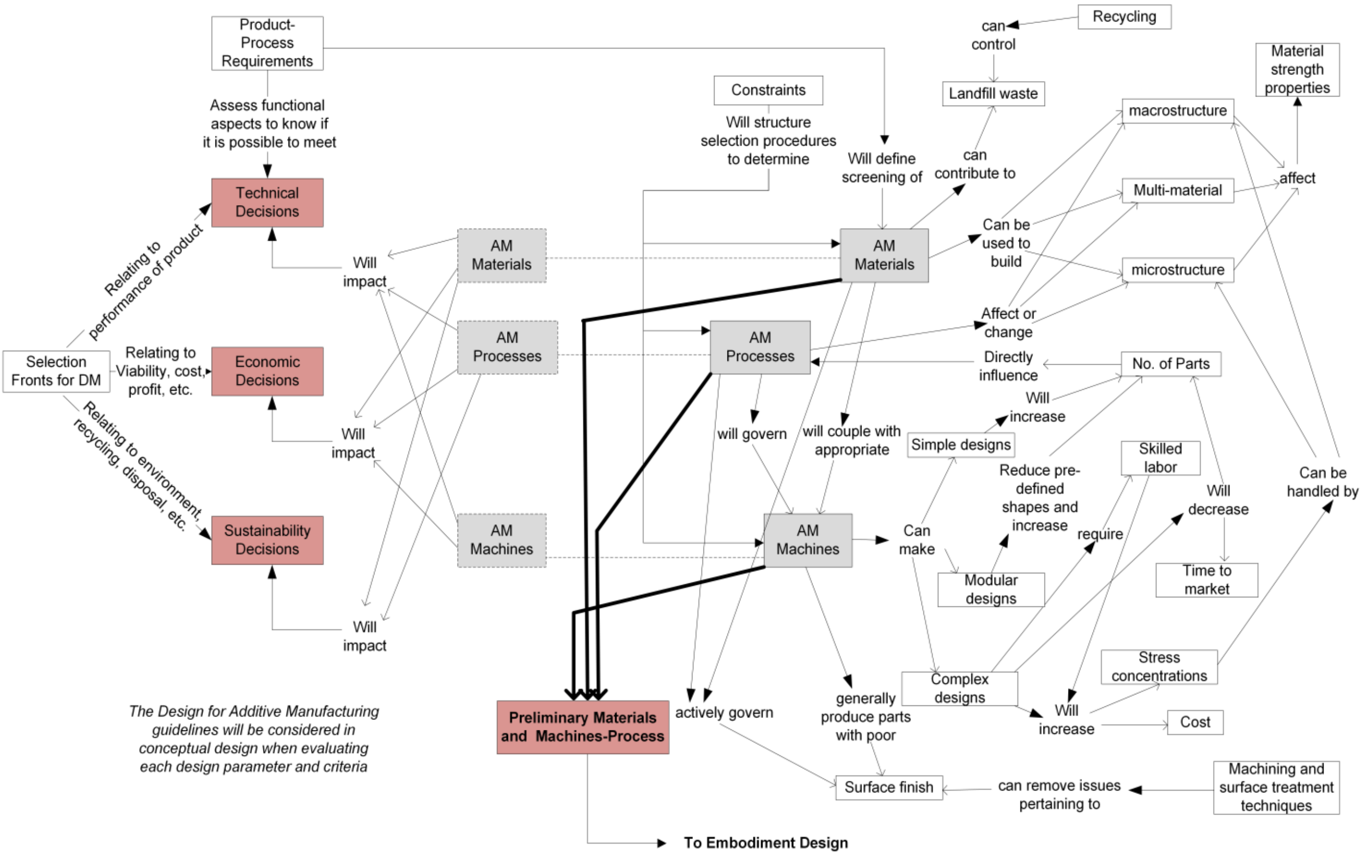

Fig. 3. Conceptual design decision space for RS in AM: An Example (developed by authors)

As shown in Fig. 3, the AM materials and processes impact all 3 decisions. However, AM machines only impact technical and economic decisions since the current study is analyzing environmental aspects related to materials and processes only. Moreover, the generated product-process requirements directly impact the decisions and AM materials, while the constraints structure the selection procedures to determine the resources.

The decision hierarchy of Fig. 3 is based on Fig. 1 and shows how some of the many possibilities can interact amidst multiple criteria, attributes and deliverables. The result of the conceptual design stage includes the release of preliminary materials and machine-process combinations for AM to the embodiment design stage.

2.2. RS in Embodiment Design

The embodiment design stage is referred to as the 'detailed inspiration' wherein a design is developed in accordance with engineering and economic criteria. However, in the proposed framework, the subject stage governs the screening and ranking of the obtained results from Sec 2.1. The databases, design attributes (along with design guidelines for each design criteria) and MCDM tool(s) are further used to get the final combination(s) of AM materials, machines and processes along with the application of a cost model. The cost model was used to calculate the overall material cost and was adopted by Yim and Rosen [34] as given below:

$$M = K_s \, . \, K_r \, . \, N \, . \, v \, . \, C_m \, . \, \rho \qquad (1)$$

where, M = overall material cost (US$), K_s = support structure factor, K_r = recycling factor, N = number of parts, v = part volume (mm^3), C_m = material rate per unit weight (US$/kg) and ρ = material density (kg/mm^3). K_s is used to capture cost of additional material usage for building support structures and is usually in the range of 1.1 – 1.5 while K_r is used to find the cost contribution of wasting loose powder which is not recycled after the build. K_r usually lies in the range of 1 – 7.

2.3. Axioms for design criteria: Environment (Example)

The axioms defined in the framework related to environment as a design criterion are many, but few are listed below [33]:

- Avoid toxic or harmful materials
- Avoid additives that emit harmful and toxic substances
- Avoid materials which emit harmful and toxic substances during disposal
- Use renewable materials
- Use materials with low energy consumption

The axioms stated above are very generic in nature and may not help the decision makers to reach a feasible solution. Therefore, rules were extracted based on IF-THEN representation. For example, for the first axiom "Avoid toxic or harmful materials", the decision tree looks like as shown in Fig. 4. The acceptance and rejection rules for the shaded strings in Fig. 4 are as shown below:

- IF the AM material is not toxic and harmful
  AND the material is recyclable
  OR the material is renewable
  OR the material is biodegradable
  THEN use the material
- IF the material is not toxic and harmful
  AND the material is not recyclable
  AND the material is not renewable
  AND the material is not biodegradable
  THEN the material can be scraped/retrieved
- IF the material can be scraped/retrieved
  AND the material has high energy consumption
  THEN avoid the material

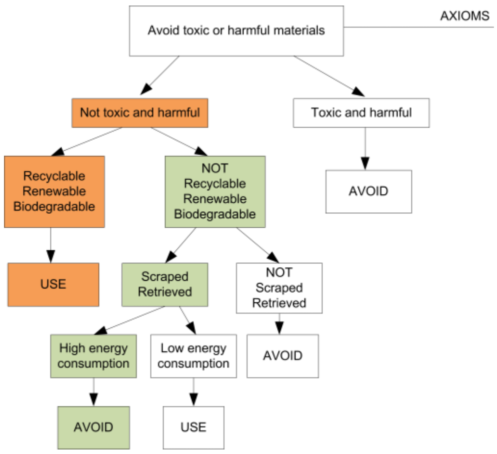

Fig. 4. Decision tree for axiom "Avoid toxic or harmful materials" (modified from Zarandi et al., 2011)

3. Example

To validate the decision-making system of the proposed framework, an example of a crank was chosen (see Fig. 5). This part is used in high speed motor applications for mechanical power (low power applications). It is assumed that the working environment may be rough.

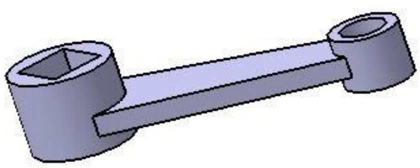

Fig. 5. Crank

Since volume of most of the building chambers of AM machines are in X, Y and Z dimensions, the volume of the part was taken as a cuboid (60x16x17) mm^3. The objective was to minimize weight, maximize strength and make the product recyclable. Two design criteria; function and environment, were hence, considered. The constraints included dimensional tolerance of 1/10 mm and part build up using a polymer. The part can be modeled as a 'column' for ease of application during conceptual design phase. The potential, 'Complexity for free', was used in this case (see Fig. 1) and the measure, 'reduce weight', was further explored in the decision space of conceptual design. Two decision fronts; technical and sustainability, were considered for the example part (see Fig.3). The material attributes included material strength properties, surface finish, environmental impact and landfill waste, while the machine attributes included geometry complexity, accuracy, minimum layer thickness, build volume, and build speed. For the sake of simplicity, only the results of each stage are shown and discussed.

3.1. RS in Conceptual Design

In view of the functional requirements of the part, the product-process requirements were generated using Ashby's material and process indices related to weight reduction and increasing stiffness of a column [35]. As shown in Sec. 2, various axioms and rules were defined with respect to the two design criteria; function and environment. Table 1 shows the preliminary materials and machines-processes (see Fig. 2) for the RS of an illustrative example.

Table 1. Preliminary AM materials, machines and processes

Sr. No.	Material	Process	Machine
1	ABflex	DLP	P4 Standard XL
2	VisiJet FTX Green	SLA	ProJet 1200
3	RGD 430	MJM	Objet 30 Pro/350/500 Connex3
4	Invicta 977	SLA	XFAB
5	Vitra 429	SLA	XFAB
6	ABS M30	FDM	Fortus 380/450/900 mc
7	VisiJet M5 Black	MJM	ProJet 5000
8	ASA	FDM	Fortus 380/450/900 mc
9	ABSPlus	FDM	µPrint SE/SE Plus, Dimension Elite
10	VisiJet M3 Black	MJM	ProJet 3600
11	ABS-ESD7	FDM	Fortus 380/450/900 mc
12	Duraform EX	SLS	sPro 140/230/60 HD-HS
13	Accura 25	SLA	ProX 800/950
14	VisiJet SL Tough	SLA	Projet 6000/7000 HD
15	PC ABS	FDM	Fortus 380/450/900 mc
16	Accura PP White	SLA	ProX 800/950
17	Duraform_PA	SLS	sPro 140/230/60 HD-HS
18	RGD 450	MJM	Objet 30 Pro/350/500 Connex3
19	R11	DLP	P4 Standard XL
20	R5 Gray	DLP	P4 Standard XL
21	ABStuff	DLP	P4 Standard XL

SLA: Stereolithography, DLP: Digital Light Processing, FDM: Fused Deposition Modeling, MJM: Multi-jet Modeling, SLS: Selective Laser Sintering

3.2. RS in Embodiment Design

This stage used AHP as a MCDM tool to screen and rank the material-machine and process combinations generated from Sec. 3.1. Table 2 shows the final RS which can be sent to the detailed design stage. Any of the obtained combinations can be used by the customer.

Table 2. Final RS for AM

Sr. No.	Material	Process	Machine
1	R11	DLP	P4 Standard XL
2	Duraform_PA	SLS	sPro 140/230/60 HD-HS
3	RGD450	MJM	Objet 30 Pro/350/500 Connex3
4	Accura PP White	SLA	ProX 800/950
5	PC ABS	FDM	Fortus 380/450/900 mc

4. Conclusions

A generic integrated design oriented framework was presented in this paper to suggest the best compromise of material(s), manufacturing process(es) and machine(s) for AM. The concept of IPPD was used to assist in providing output in the form of reduced costs, increased functional performance, and sustainability. The proposed framework worked intensively in the conceptual and embodiment design stages via defined axioms and extracted rules to produce a healthy blend of RS for AM. An example case was also used to validate the framework along with the proposal of relevant material, process, and machine combinations. Furthermore, the framework followed the standard translation, screening and ranking procedures. It was an intensive design task that can be employed to implement procedures in conjunction with the DfAM guidelines, application type, functional constraints, and part requirements. Finally, the generated AM materials, processes and machines provided sufficient opportunity for the consumer to try multiple combinations as per constraining factors such as budget.

References

[1] Ranjan R, Samant R, Anand S. Design for manufacturability in additive manufacturing using graph based approach. Proceedings of ASME 2015 International Manufacturing Science and Engineering Conference, Charlotte, North Carolina, USA, 2015; doi:10.1115/MSEC2015-9448.

[2] ASTM. Standard Terminology for Additive Manufacturing Technologies, Standard F2792-12a, ASTM International, West Conshohocken, PA, 2012, doi: 10.1520/F2792-10, www.astm.org.

[3] Monzon MD, Ortega Z, Martinez A, Ortega F. Standardization in Additive Manufacturing: Activities Carried out by International Organizations and Projects. International Journal of Advanced Manufacturing Technology 2014; 76(5-8): 1111-1121.

[4] Huang Y, Leu MC, Mazumder J, Donmez A. Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of Manufacturing Science and Engineering 2015; 137: 014001/1 – 014001/10.

[5] Vaezi M, Chianrabutra S, Mellor B. Multiple material additive manufacturing-part 1: a review. Journal of Virtual and Physical Prototyping 2013; 8(1): 19-50.

[6] Cozmei C, Caloian F. Additive Manufacturing Flickering at the Beginning of Existence. Procedia Economics and Finance 2012; 3: 457-462.

[7] Hague R, Mansour S, Saleh N. Design Opportunities with Rapid Manufacturing. Journal of Assembly Automation 2003; 23(4): 346–356.

[8] Hopkinson N, Dickens P. Emerging Rapid Manufacturing Processes. In: Rapid Manufacturing-An Industrial Revolution for the Digital Age 2006, John Wiley, Chichester: 55-80.

[9] Kuo TC, Huang SH, Zhang HC. Design for Manufacture and Design for 'X': Concepts, Applications and Perspectives. Journal of Computers and Industrial Engineering 2001; 41: 241-260.

[10] Rosen DW. Computer-aided design for additive manufacturing of cellular structures. Computer-Aided Design and Applications 2007; 4(1-6): 585-594.

[11] Adam GA, Zimmer D. Design for Additive Manufacturing-Element transitions and aggregated structures. CIRP Journal of Manufacturing Science and Technology 2014; 7(1): 20-28.

[12] Ponche R, Kerbrat O, Mognol P, Hascoet JY. A novel methodology of design for Additive Manufacturing applied to Additive Laser Manufacturing process, International Journal of Robotics and Computer Integrated Manufacturing 2014; 30: 389–398.

[13] Yazdi EA, Gardan J, Lafon P. Integrated design for additive manufacturing based on skin-skeleton approach. Procedia CIRP 2017; 60: 217-222.

[14] Salonitis K, Zarban SA. Redesign optimization for manufacturing using additive layer techniques. Procedia CIRP 2015; 36: 193–198.

[15] Klahn C, Leutenecker B, Meboldt M. Design Strategies for the Process of Additive Manufacturing. Procedia CIRP 2015; 36: 230-235.

[16] Thompson MK, Moroni G, Vaneker T, Fadel G, Campbell RI, Gibson I, Bernard A, Schulz J, Graf P, Ahuja B, Martina F. Design for Additive Manufacturing: Trends, Opportunities, Considerations and Constraints. CIRP Annals – Manufacturing Technology 2016; 65: 737-760.

[17] Zaman UKU, Siadat A, Rivette M, Baqai AA, Qiao L. Integrated Product-Process Design to Suggest Appropriate Manufacturing Technology: A Review. International Journal of Advanced Manufacturing Technology 2017; 91 (1-4): 1409-1430.

[18] Wang Y, Blanche R, Xu X. Selection of additive manufacturing processes. Rapid Prototyping Journal 2017; 23(2): 434-447.

[19] Ashby MF. Material and Process Charts. The CES EduPack Resource Booklet 2, © Granta Design 2009.

[20] Berman AF, Maltugueva GS, Yurin AY. Application of Case-Based Reasoning and Multi-Criteria Decision Making Methods for Material Selection in Petrochemistry. Journal of Materials, Design and Applications 2015: 1–9.

[21] Kesteren VIEH, Stappers PJ, De Bruijn JCM. Materials in product selection: tools for including user-interaction in materials selection. International Journal of Design 2007; 1(3):41–55.

[22] Ipek M, Selvi IH, Findik F, Torkul O, Cedimoglu IH. An expert system based material selection approach to manufacturing. Journal of Materials and Design 2013; 47:331–340.

[23] Mancanares CG, Zancul ES, Silva JC, Miguel PAC. Additive Manufacturing Process Selection Based on Parts' Selection Criteria. International Journal of Advanced Manufacturing Technology 2015, doi: 10.1007/s00170-015-7092-4.

[24] Armillotta A. Selection of Layered Manufacturing Techniques by an Adaptive AHP Decision Model. Robotics and Computer-Integrated Manufacturing 2007; 24: 450-461.

[25] Zaman UKU, Rivette M, Siadat A, Mousavi SM. Integrated product-process design: material and manufacturing process selection for additive manufacturing using multi-criteria decision making. Robotics and Computer Integrated Manufacturing 2018; 51: 169-180.

[26] Emrouznejad A, Marra M. The state of the art development of ahp (1979-2017): a literature review with a social network analysis. International Journal of Production Research 2017; doi:10.1080/00207543.2017.1334976.

[27] Yazdani M, Jahan A. Analysis in material selection: influence of normalization tools on COPRAS-G, Economic Computation and Economic Cybernetics Studies and Research 2017; 51 (1): 59–74.

[28] Adhikari PR, Mirshams R. Study of knowledge-based system (KBS) and decision–making methodologies in materials selection for lightweight aircraft metallic structures. Journal of Applied Science Engineering and Technology 2017; 5 (1): 1–19.

[29] Lukic D, Milosevic M, Antic A, Borojevic S, Ficko M. Multi-criteria selection of manufacturing processes in the conceptual process planning. Advances in Production Engineering and Management 2017; 12 (2): 151–162.

[30] Gupta SK, Chen Y, Feng S, Sriram R. A system for generating process and material selection advice during embodiment design of mechanical components. Journal of Manufacturing Systems 2003; 22(1):28-45.

[31] Zarandi MHF, Mansour S, Hosseinijou SA, Avazbeigi M. A material selection methodology and expert system for sustainable product design. International Journal of Advanced Manufacturing Technology 2011; 57: 885-903.

[32] Deng Y-M, Edwards KL. The role of materials identification and selection in engineering design. Journal of Materials and Design 2007; 28: 131–139.

[33] Albinana JC, Vila C. A framework for concurrent material and process selection during conceptual product design stages 2012; 41: 433-446.

[34] Yim S, Rosen D. Build Time and Cost Models for Additive Manufacturing Process Selection. Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, IDETC/CIE, 2012; Chicago, USA.

[35] Ashby MF. Materials Selection in Mechanical Design. Third Edition, Butterworth-Heinemann Linacre House, Jordan Hill, Oxford, UK, 2005, ISBN: 0-7506-6168-2.